

Experimental and Analytical Investigation of Mine Burial Penetration

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LONG-TERM GOALS

The goal of this project is to develop a method for calculating the depth of penetration of mines into soft cohesive sediments, and, if necessary, to simplify the predictive method to render it suitable for Fleet use.

OBJECTIVES

The primary objective is to develop a sound theoretical/analytical model that will accurately predict the penetration depth of objects landing on a soft cohesive seafloor.

APPROACH

The subject study involves parallel experimental and analytical studies of mine penetration in cohesive seafloor sediments as follows:

- Model tests in a laboratory test basin of mines penetrating in actual (Gulf of Mexico) seafloor sediments. This effort will be directed by Dr. Wayne Dunlap.
- Numerical modeling of the mine penetration process. This effort will be directed by Dr. Charles Aubeny with technical support provided by Dr. Richard Schapery, University of Texas-Austin.
- After calibration of the numerical model to the test measurements, a simplified model will be proposed for use in practice. Drs. Dunlap, Aubeny and Schapery will participate in this effort.

WORK COMPLETED

Experimental Studies:

Collection of Gulf of Mexico Cohesive Sediments- On May 23-27 Drs. Wayne Dunlap and Charles Aubeny and graduate students Zhigang Yao and Muhammed Munim traveled to Port Aransas, Texas for the purpose of collecting cohesive Gulf of Mexico marine sediments to be used in the experimental

mine penetration tests. Offshore sampling was conducted on the R/V *Longhorn*. Approximately 20 miles south of Port Aransas, a site within the “wedding cake” mine drop practice area which was likely to have cohesive seafloor sediments was identified and box core sampling was initiated. Initial sampling identified the seafloor sediments to be comprised of medium plasticity clays with varying percentages (typically less than 50%) of fine sand. Suitable sediment samples were loaded into 55 gallon drums. Typically 2 to 3 box core samples were required to fill one drum. Drs. Dunlap and Aubeny continuously monitored the samples to ensure that clayey sediments were being collected. Much sandier sediments occurred a relatively short distance (hundreds of feet) from the original sampling location, indicating that a relatively high degree of soil variability can occur at this site. Only plastic clays having less than 50% sand (based on visual judgement) were collected for the experimental model tests. Two work days were required to collect a total of 35 drums of sediment. The drums were then transported to the Offshore Technology Research Center (OTRC) at Texas A&M University in College Station.

Processing of Sediments- To be suitable for the model tests, the sediments needed to be processed to (1) remove shells or other oversize materials that could adversely influence the model tests, (2) achieve uniformity with regard to material type and moisture content, and (3) achieve a moisture content corresponding to an undrained shear strength of about 25 psf. The time required to screen, mix, and dry the required volume of sediment to achieve a suitable material for the model tests was about 8 weeks.

Oversize materials, which were primarily shells, were removed by manual screening. Although the volume of shells collected was relatively small, the possibility that a shell could occur at a critical location during the mine penetration tests required that all material be screened. After the initial screening, the sediments were unloaded into four large basins for mixing and drying the sediment. To maximize the mixing, sediments from the same drum were distributed into different basins. Thorough mixing in the basins was achieved manually. Uniformity of material type was monitored by random sampling and laboratory testing to determine the percentage of particle sizes passing the No. 200 sieve (fines content). Uniformity of moisture content was monitored by laboratory moisture determinations and manual vane shear tests. After mixing the average fines content from random sampling was 69.5% with a standard deviation of 6.6%. Given the relatively large volume of material that is being handled, this is considered an acceptable level of variability.

The average moisture content of the collected sediment was about 69%, which corresponds to an undrained shear strength well below 10 psf. The target shear strength for the model tests is about 25 psf corresponding to a moisture content of about 50%; therefore, the sediments were aired outdoors to achieve these target values. Due to the tendency for non-uniform drying the sediment was re-mixed several times daily. The rate of drying of the sediments largely controlled the overall timetable for processing of the sediments, which required about 8 weeks to produce the required volume for the experimental model tests.

Test Basin and Associated Apparatus- A test basin for the laboratory mine penetration tests has been fabricated. The basin is 6 ft in diameter and 4 ft high. For the initial tests, a frame system designed to provide control over (1) the weight of the mine, and (2) the orientation of the mine has been mounted on the basin. Both of these parameters, weight and mine orientation, will be varied in the initial mine penetration experiments. A displacement transducer (LCDT) will be attached to the frame to measure a continuous time history of penetration. These data will be used with the analytic models described below for purposes of model validation and calibration. After these initial tests are completed, free fall penetration tests will be conducted.

After each mine penetration test, the sediment will be re-worked and smoothed. Re-working will be accomplished with a drill-mounted stirrer while smoothing the surface of the re-worked sediment will be accomplished by a rotating screed attached to the frame assembly. Each model mine penetration test will be conducted 24 hours after re-working and smoothing the sediment. Past experience has shown that most of the thixotropic strength gain effects occur during this time period.

The model mines will have dimensions approximating those of the models used for the Carderock tank tests (6.625 inch diameter by 19.875 inches long). The weights of the mines will bracket the weight range used in the Carderock tests (37.40 to 49.09 lbs). In the initial tests symmetric mine shapes will be used, which are comprised of a cylindrical section with hemispherical ends. This is in contrast to the Carderock model mines and actual mines. However, symmetrical model mine shapes are preferable for initial studies to provide an unambiguous basis for validating and calibrating the analytical and numerical models. The cylindrical portion of the model mine will be fabricated from aluminum tubing while the hemispherical end sections will be milled from plastic.

Analytical Studies:

Finite Element Model- Finite element simulations provide a means of obtaining quantitative predictions of mine penetration. These numerical simulations provide a valuable complement to the experimental studies, since a much wider range of soil and geometric variables can be investigated than can feasibly be done in an experimental program. Finite element simulation of the mine penetration process is particularly complex, due to the following aspects of the problem:

- The problem geometry is three-dimensional.
- The soil-mine boundary interface varies throughout the penetration process; this type of problem is known as a contact problem.
- The problem is also geometrically non-linear due to the large strains and displacements occurring during the penetration process.
- The material behavior is non-linear.
- For the general problem of impact at terminal velocity, inertial effects must be considered.

The finite element code ABAQUS being used in this study has capabilities for modeling the complexities described above. However, even in a well-documented commercial code such as ABAQUS highly non-linear processes such as mine penetration require a considerable degree of validation to ensure that the model is working properly. One means of validation is to simplify the problem to one for which an analytical solution exists and compare the finite element predictions to the exact analytical predictions. Aside from ensuring that no errors exist in the model, this process

provides an indication of the overall degree of numerical accuracy that can be expected from the finite element model. When increasingly complex analyses are attempted, no such validation is possible; hence, the simplified analyses provide the most reliable means of detecting errors and numerical difficulties in the model.

Two models for constitutive (stress-strain) behavior of the sediment are being considered at present: the viscous fluid power law model used in the dimensional analysis discussed later and a rate-dependent plasticity model. The viscous model has the limitation that soil resistance can only be mobilized when the mine is moving; hence, the velocity of a penetrating mine will never decline to zero. While this is obviously not realistic, the viscous model can nevertheless simulate important aspects of the penetration process. The ABAQUS code is capable of modeling both types of constitutive behavior.

RESULTS

Geotechnical Characterization of Sediments:

A series of geotechnical laboratory tests were conducted to:

- Provide accurate data for soil classification and index tests. Tests performed for this purpose were sieve analysis, Atterberg limits, and specific gravity. Any comparisons of model test data to future field tests must take variations in soil type into account; hence, reliable classification data are essential. The classification test data are summarized in Table 1. The sediment can be characterized as a sandy, medium plasticity clay having a group symbol CL in the Unified Soil Classification System.
- Establish a relationship between undrained shear strength and moisture content. Undrained shear strength will be the single most important soil property controlling the resistance of the soil to mine penetration; hence, reliable determinations of this parameter are essential to interpretation of experimental data. With a well-defined moisture content-shear strength relationship, shear strength can be estimated from simple moisture content determinations taken after each model mine penetration test. Strength estimates based on this method will be supplemented by hand-operated vane shear tests. The strength-moisture relationship was established based on miniature vane shear and hand-operated vane shear tests on sediment samples followed by moisture content determinations.
- Determine the rate dependent strength properties of the sediments. Due to the relatively rapid rate of penetration of the mine into the sediments, the rate dependent properties of the soil are likely to significantly affect penetration and need to be incorporated into the mine penetration model. To establish rate dependent strength properties, a miniature vane apparatus having capabilities for a variable vane rotation rate was fabricated. Based on strength measurements at different vane rotation rates (strain rates), rate dependent (viscous) parameters can be back-calculated.

Dimensional Analysis:

By characterizing the sediment as a viscous power law fluid, Dr. Richard Schapery, a consultant to this project, performed a dimensional analysis of the variables controlling mine penetration. Dimensional

analysis provides a useful framework for plotting and interpreting experimental parameters and measurements. His results indicate that the depth of penetration h can be described as follows:

$$h/D = f(\lambda_1, \lambda_2, \lambda_3, \lambda_4, n, \theta)$$

where h = depth below mudline
 D = mine diameter
 f = dimensionless function
 θ = orientation of mine
 n = exponent in viscous power law equation

The λ_i factors are defined as:

$$\lambda_1 = W v^{2-n} / g \tau_0 \theta' D^{3-n}$$

$$\lambda_2 = \gamma D^3 / W$$

$$\lambda_3 = W v^{-n} / \tau_0 \theta'^{-n} D^{2-n}$$

$$\lambda_4 = D/L$$

where W = mine weight
 v = impact velocity
 g = gravitational acceleration
 τ_0 = soil resistance at reference strain rate
 D = mine diameter
 L = mine length
 θ' = angular velocity of mine at impact

Based on these dimensional analyses, a matrix of the planned experimental program was developed as shown in Table 2.

Finite Element Analysis:

The present status of the finite element studies is: (1) three-dimensional meshes describing the problem geometry have been developed, (2) the simplified problem of a vertically oriented mine has been solved and found to adequately match analytical bearing capacity solutions, and (3) development of the variable soil-mine interface model is currently in progress.

IMPACT/APPLICATIONS

A sound theory has not been developed for prediction of penetration depth of objects dropped onto soft rate-dependent sediments. The results from this project should allow penetration depth to be accurately calculated. This will not only benefit the Navy, it should also be helpful to industrial interests, especially the offshore petroleum industry.

TRANSITIONS

Since this project is in the early stages of development, there are no products at present for others to use.

RELATED PROJECTS

No other projects are presently developing predictive methods for impact mine burial in cohesive sediments. However, the projects being conducted by NRL on behavior of mines in the water column is expected to provide significant data regarding mine orientation when mines initially penetrate the sediment.

Table 1. Sediment Classification Test Properties

Plastic Limit	Liquid Limit	Percent Fines
21	44	69.5

Table 2. Test Plan for Mine Penetration Tests

	Mine Weight (lbs)		
Initial % Penetration	37.4	49.09	60.0*
0	X	X	XX
$\frac{1}{4}$	X		X
$\frac{1}{2}$		XX	X
1	XX		X

*Weight may be adjusted subject to results of 37.4 and 49.09lb test series.

X- single test will be performed, XX – Replicate test will be performed.